# PLASMA LENS FOR MANIPULATING LARGE AREA HIGH-CURRENT ELECTRON BEAMS

***A. Goncharov[1], A. Dobrovolskiy[1], I. Litovko[2], V. Gushenets[3], E. Oks[3], A. Bugaev[3]***
***[1]Institute of Physics, NASU, Kiev, Ukraine;***
***[2]Institute for Nuclear Research, NASU, Kiev, Ukraine;***
***[3]High-Current Electronics Institute, SB of RAS, Tomsk, Russia***
***E-mail: gonchar@iop.kiev.ua***

We describe the current status of ongoing research and development of the wide aperture electrostatic plasma lens with positive space charge cloud for focusing and manipulating large area high current electron beams. It is presented new theoretical and experimental results of wide-aperture (diameter 6 cm), non-relativistic (up to 20 keV) high-current electron beam (current up to 100 A) manipulating by the electrostatic plasma lens.

PACS: 52.65.-y

## INTRODUCTION

Progress in development of high – current negative ion sources is an incitement to creation of new focusing tools for intense negatively charged particle beams manipulation. Using a positive space charge for that purpose appeared to be a very successful concept. The first plasma lens with positive space charge for these aims is based on the principle of electrostatic electron isolation [1]. Experimental investigations of the positive space charge electrostatic plasma lens have demonstrated the principal possibility to create the positive space charge cloud for negative ion beam focusing [2]. This device is easily-maintained and low-cost; but obtaining a strong electric field (more than 100 V/cm) is its limitation.

Later [3] it was proposed to use magnetic electron insulation for creation of the positive space charge stable cloud. The original device has been designed for this purpose. It has been investigated both experimentally and theoretically [4 - 6].

For relatively low-current mode for which electron beam space charged less than positive space charged plasma lens it realize electrostatic focusing passing electron beam [7]

In case of high-current mode when electron beam space charge much more than space charge plasma lens the lens operates in plasma mode to create transparent plasma accelerating electrode and compensate space charge propagating electron beam. The lens magnetic field in this case uses for effective focusing beam. Under described experimental conditions the maximal compression factor was up to 30 and beam current density at the focus was about 100 A/cm$^2$ [8].

This paper describes new computer simulation results of a wide-aperture (diameter 6 cm), non-relativistic (up to 20 keV) high-current electron beam (current up to 100 A) transported through an axially symmetric device with a positive space charge plasma lens. And also we describe the advance plasma lens configuration with magnetic azimuthally compensator.

## 1. EXPERIMENTAL SETUP AND RESULTS

The experiments on high-current electron beam (energy 20 keV and current up to 100 A) focusing by the lens with a positive space charge have been detailing described in [8]. It was carried out on a setup that is shown in Fig. 1. An electron beam (8) from the electron source (1 - 4) passes through the plasma lens volume (5 - 7) to the sectioned collector (9-13), where the electron beam current distribution along radius has been analyzed.

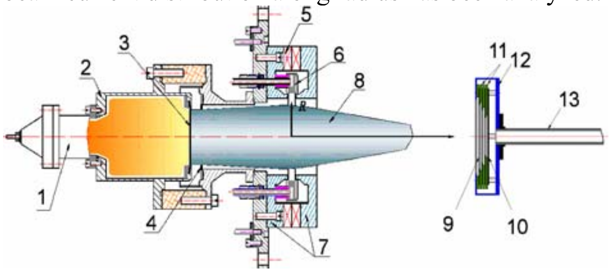

*Fig. 1. The scheme of the setup: 1 – plasma electron source; 2 – hollow anode; 3 – emission grid; 4 – accelerating electrode; 5 – permanent magnets; 6 – anode; 7 – cathode; 8 – electron beam; 9,10 – collector rings; 11 – isolators; 12 – shield; 13 – slide rod*

In these experiments the lens discharge current was above 100 mA, pressure above 4×10$^{-4}$ Torr. The lens was operated in the continuous (dc) mode. The discharge current was limited by the power scattered by the electrodes. It allowed compressing the electron beam from its initial diameter of 6 cm to a diameter of 1 cm; the current density thus increased more than 30 times and was larger than 100 A/cm$^2$.

Before we had shown that at an electron beam current greater than 1 A, the potential in the positive space charge region decreases and the region collapses [3, 5]. This breaks down the electrostatic focusing, and only the magnetic focusing of the beam survives. But producing additional plasma density by plasma lens will compensate space charge propagating electron beam and promote for the stable transport of the intensive electron beam.

## 2. SIMULATION RESULTS OF HIGH-CURRENT ELECTRON BEAM FOCUSING

Early we create theoretical and numerical model for simulation plasma lens space charge creation and transport negatively charged particle beams through such kind plasma lens detail described in [3 - 5]. But for simulation high-current electron beam transport need take into account the importance the space charge of the particles (ρ) in addition to the external fields:

$$\rho = \sum_{i=1}^{N} \frac{j_i}{v_i}$$

and the magnetic self-field (B) that may influence the beam particles themselves:

$$B = \mu_0 \mu_r \frac{j}{r},$$

where $j_i$ is current density, $v$ – velocity, $N$ is maximum charge of ions in the beam, $\mu_0\ \mu_r$ – the permeability and $r$ is the perpendicular distance to the trajectory.

As we have shown before [2, 4, 5] if beam space charge density equals or exceeds space charge cloud density – cloud quickly destroys and $Ar^+$-ions continuing to come from anode layer couldn't reconstruct it. Electron beam with current larger 1 A take away with one significant part of cloud particles that decrease cloud potential and PL (plasma lens) focusing properties has been destroyed. The situation could be improved with increasing energy and current density ion beam that positive space charge cloud created. It is shown in Fig. 2. Here are shown electron beam trajectories under passing electron beam with current ($I_{eb}$) 10A and energy ($E_{eb}$) 10 keV through PL with lens potential ($U_L$) 2.4 kV and magnetic field (H) about 50 Oe on the axis with increasing $Ar^+$-ion beam ($I_{ib}$) current from 20 mA (top) to 80 mA (down). Ones can see that focusing properties of plasma lens had been recovered.

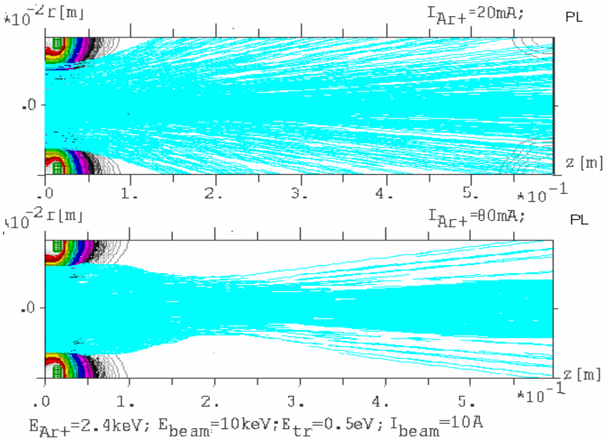

*Fig. 2. Electron beam trajectories under increasing $I_{ib}$ of $Ar^+$-ions from 20 mA (top) to 80 mA (down)*

However for electron beam with current on the order of tens ampere when the beam space charge density much more than space charge plasma lens could operate only magnetic focusing. Plasma lens continuing to produce positive ion beam will compensate space charge propagating electron beam and thus assists for the stable transport of the intensive electron beam. Really as shown in Fig. 3 the electron beam traped $Ar^+$-ions along.

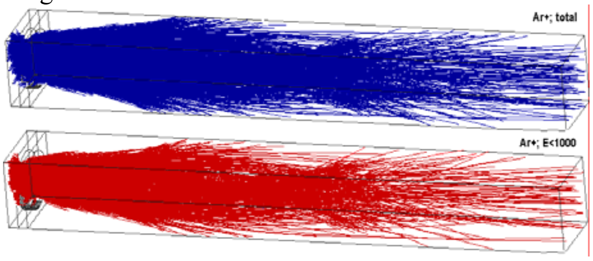

*Fig. 3. 3D-trajectories of Ar+-ion pull along by electron beam ($E_b$=20 keV, $I_b$=100 A, alpha=0.5) passing through PL: all-energies (top) and low-energy (down)*

Majority of them is low-energy ions (E<1 kV). According to our simulation the beam is dragging $Ar^+$-ions, coming to volume, along and almost 70% from them are low-energy.

Thus the PL role reduce to producing additional compensate space charge in this case and for best beam focusing we need properly increase magnetic field. We increase magnetic field almost twice as compared with previous calculation and it reach about 120 Oe on the axis.

In our simulations we took into account only the lens-produced plasma for compensation of the space charge of the electron beam and disregarded the plasma produces by electron beam itself through ionization of the gas supplied and desorbed from the walls of the transport channel. We considered the electron beam with space charge compensation parameter (alpha) 0.5 and 0.8. The density of the lens-produced plasma (in our calculation is regarded $U_L$=2.4 kV, I=100 mA) for case alpha=0.5 is insufficient for compensation of the space charge of the electron beam and the beam partly lost on the calculation box that could be see in Fig. 4. Here is submitted simulated electron beam trajectories ($E_{eb}$=20 keV, $I_{eb}$=100 A, space-charge beam compensation parameter is 0.5) passing through ML(magnetic lens) (top) and PL with the same magnetic field (down). Ones can see that switching on PL reduce beam divergence. Another result is reducing beam losses. The beam current through-passing on the end of calculation box increases from 47 A for PL-off case to 55 A for PL-on case for alpha=0.5.

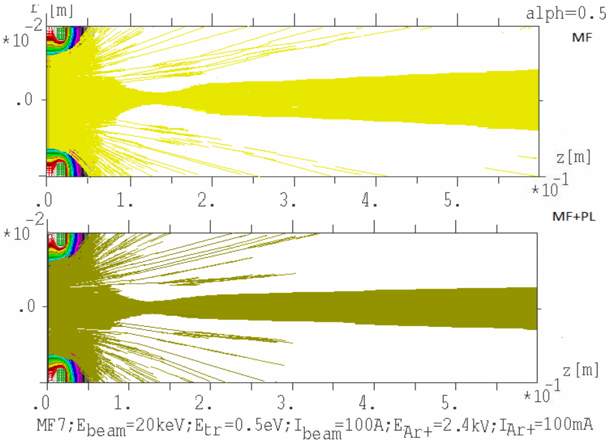

*Fig. 4. Electron beam trajectories under passing through ML (top) and PL (down). H~ 120 Oe on the axis*

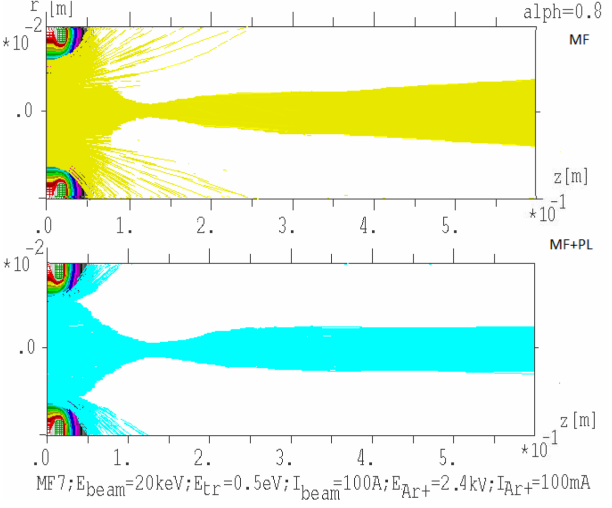

*Fig. 5. Electron beam trajectories(alpha=0.8) under passing through ML (top) and PL (down). H~ 120 Oe*

In the Fig. 5 is shown electron beam trajectories calculated for beam compensation parameter alpha=0.8. Here beam losses are significantly less and $Ar^+$-ions produced by plasma lens are almost sufficient for electron beam space charge compensation. We can see that when PL on the beam divergence is smaller as result dragging additional numbers positive ions Ar along beam line. Our simulation demonstrates the presence of space charge PL enhances beam focusing in comparison with magnetic focusing only. Thus the switching on PL reduces beam losses and improves beam transport.

## 3. ADVANCED PLASMA LENS

Our first realization of plasma lens with magnetically isolation of electrons and separation of areas of ionization and accumulating a space charge have essential disadvantage. The potential distribution have clear gap around the axis of cylindrical symmetry [4]. One way of eliminating this problem is use of magnetic azimuthally compensator [5, 9]. Other way is use heavy gas ions to minimize an impact of magnet field. Here we present the plasma lens with double channel magnetic system. One channel, nearest to anode, is discharge channel and second is compensator of azimuthal twist of accelerated ions. The Fig. 6 shows a schema of plasma lens. The lens is a cylindrical convergent plasma accelerator with an anode layer and used as a device with magnetic insulation of electrons for creation of the dynamic cloud of positive space charge. The beam of positively charged argon ions form by the device in first channel and converge to the system axis whereas electrons were magnetized in the anode layer. In the second channel ions impact by reversed magnetic field and go toward center the system. The lens has a system of permanent magnets (3) that produces an axially symmetric magnetic field between the poles of a magnetic circuit serving as cathode. The magnetic field is controlled by varying the number of magnets or by using magnetic shunts. In the positive ions accumulating area exist diffuse magnetic field. Because the magnetic field configuration is typical for single magnetic lens configuration, the lens will partially focus the transported electron beam even without electric potential applied.

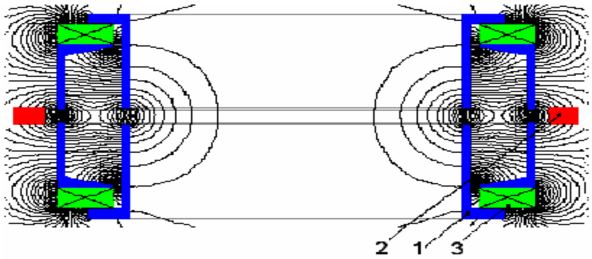

*Fig. 6. Schematic of the plasma lens with magnetic azimuthal compensator: 1) cathode; 2) anode; 3) magnetic system based on permanent magnets*

When a positive potential is applied to the anode (2), a discharge in the axial magnetic and radial electric crossed fields is ignited between the anode and the cathode (1). The electrons thus drift along closed trajectories in the azimuthal direction, repeatedly ionize atoms of the working gas (Ar), and gradually diffuse to the anode. The ions thus formed are accelerated in the strong electric field created by the electron space charge and leave the ion source through a hole in the acceleration channel. The axially converging ion beam creates a positive space charge. In the experiments, the energy of the converging beam could reach 2.5 kV. Maximum potential will be in the center of system. Ions oscillate in the cylinder volume until their own space charge creates a critical electric field. This field forces ions to leave the volume and the system comes to dynamic equilibrium after some relaxation time. Thus in the region of positive space charge, an electrostatic PL arises, being suitable for focusing beams of negatively charged particles, including electrons.

The second channel with reverse magnetic field changes trajectories of ions arriving to space charge cloud. Without compensation ion go not to centre exactly (Fig. 7,a,b). First simulation shows the case without compensator and second with reverse field. For b) figure second channel placed between 40 and 50 mm.

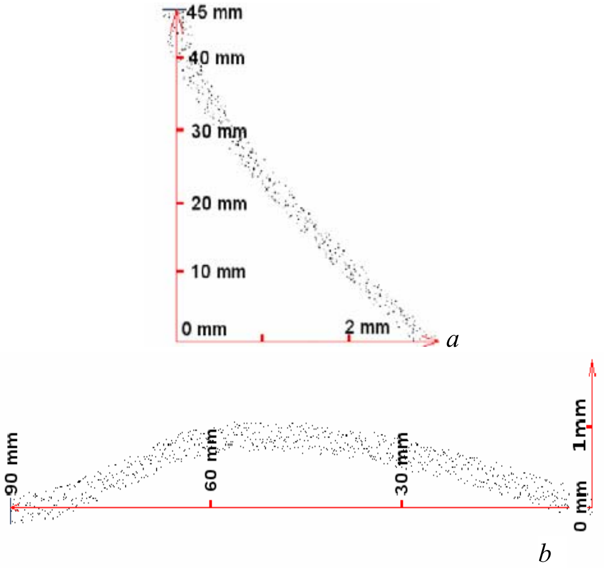

*Fig. 7. Trajectories of ions from ion source face to center of system. a) one channel model; b) with reverse magnetic field*

Such modification of magnetic system of ion source leads to significant changes in area of space charge cloud. Fig. 8 is shown the photo of lightings from space charge region of plasma lens. It is seen here absence dark spot in centre of lens, in comparison with previous observation [2].

*Fig. 8. Photo of typical lightings from space charge region of plasma lens*

Also we made measurements of floating potential distributions in space charge cloud region. The typical profile is shown on Fig. 9. It is shown map of potential in r, z coordinates. It is seen here absence the gap of potential around the axis of system. In the case of new magnetic system the smooth with one pike distribution of potential in lens volume are formed. And we have not marked spherical aberration in main volume of focused beam. This distribution correspond to anode lens potential 1200 V and pressure of Ar in chamber 7·10-5 Torr.

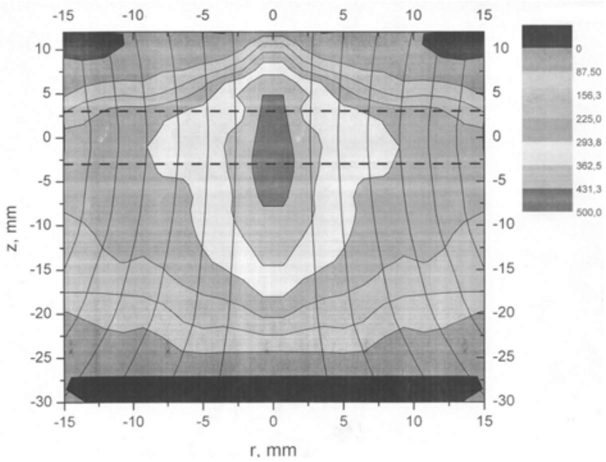

*Fig. 9. The map of potential distribution in advanced plasma lens, anode potential is 1200 V, Ar pressure 7·10$^{-5}$ Torr*

## CONCLUSIONS

Presented results demonstrate an attractive possibilities application positive space charged plasma lens with magnetic electron insulation for focusing and manipulating wide-aperture high-current no relativistic electron beams. In case of high-current mode when electron beam space charge much more than space charge plasma lens the lens operates in plasma mode to create transparent plasma accelerating electrode and compensate space charge propagating electron beam. The only lens magnetic field in this case uses for effective focusing beam. As it seen from simulation plasma lens is produced plasma density required for the electron beam stable transport. The advanced magnetic field configuration allows to eliminate momentum aberrations and to improve optical properties plasma lens.

This work was supported in part by RFBR and SFBR of Ukraine under the program of joint Russian-Ukrainian research projects (RFBR Grant №11-08-90405, SFBR Grant №F40.2/023-2011).

## REFERENCES

1. V. Goretskii, I. Soloshenko, and A. Shchedrin. Space-charge Lens for Focusing Negative Ion Beams // *Plasma Phys. Rep*. 2001, v. 27(4), p. 1.
2. A. Goncharov, A. Dobrovolskiy, S. Dunets, A. Evsyukov, V. Gushenets, V. Goretskiy, I. Litovko, E. Oks, I. Soloshenko. The Positive Space Charge Lens for Focusing and Manipulating High-Current Beams of Negatively Charged Particles (Review) // *XXIVth Int. Symp. on Discharges and Electrical Insulation in Vacuum-Braunschweig*. 2010.
3. A. Dobrovolskiy, S. Dunets, A. Evsyukov, A. Goncharov, V. Gushenets, I. Litovko, E. Oks. Recent advances in plasma devices based on plasma lens configuration for manipulating high-current heavy ion beams // *Rev. Sci. Instrum.* 2010, v. 81(2B), p. 704.
4. A. Goncharov, A. Dobrovolskiy, S. Dunets, A. Evsyukov, I. Litovko, V. Gushenets, E. Oks. Positive-Space-Charge Lens for Focusing and Manipulating High-Current Beams of Negatively Charged Particles // *IEEE Trans. Plasma Sci.* 2011, v. 39, № 6, p. 1408.
5. A.A. Goncharov, A.M. Dobrovolskiy, S.P. Dunets, I.V. Litovko, V.I. Gushenets, E.M. Oks. Electrostatic plasma lens for focusing negatively charged particle beams // *Rev. Sci. Instrum.* 2012, v. 83, p. 723.
6. A. Goncharov, A. Dobrovolsky, S. Dunets, V. Gushenets, I. Litovko, E. Oks. Plasma lens for negatively charged particle beams focusing: recent results // *Advances in Applied Plasma Science.* 2011, v. 8, p. 47.
7. A. Goncharov, A. Dobrovolsky, V. Gushenets, I. Litovko, E. Oks. Present status of the positive space charge lense for focusing intense negative charged particle beams // *Problems of Atomic Science and Technolog. Series «Plasma Physics» (82).* 2012, № 6, p. 108-110.
8. V. Gushenets, A. Goncharov, A. Dobrovolskiy, S. Dunets, V.E. Oks, A. Bugaev. Electrostatic plas-ma lens focusing of an intense electron beam in an electron source with a vacuum arc plasma cathode // *IEEE Trans. Plasma Sci.* 2013, v. 41, № 4, part. 3.
9. A.A. Bizyukov, A.I. Girka, K.N. Sereda, A.V. Nazarov, E.V. Romaschenko. Hall ion source with ballistic and magnetic beam focusing //*Problems of Atomic Science and Technology. Series «Plasma Physics» (14).* 2008, № 6, p. 174-176.

*Article received 16.04.2013*

---

## ПЛАЗМЕННАЯ ЛИНЗА ДЛЯ УПРАВЛЕНИЯ СИЛЬНОТОЧНЫМИ ЭЛЕКТРОННЫМИ ПУЧКАМИ БОЛЬШОЙ ПЛОЩАДИ

***А. Гончаров, А. Добровольский, И. Литовко, В. Гушенец, Е. Окс, А. Бугаев***

Представлены новые теоретические и экспериментальные результаты фокусировки сильноточного интенсивного электронного пучка плазменной линзой с облаком аксиально-симметричного положительного пространственного заряда, созданного цилиндрическим ускорителем с анодным слоем и магнитной изоляцией электронов. Достигнуто почти 30-кратное увеличение плотности тока пучка на оси при совместном действии магнитного и электростатического полей линзы. Предложена модифицированная конструкция плазменной линзы, устраняющая моментные аберрации.

---

## ПЛАЗМОВА ЛІНЗА ДЛЯ КЕРУВАННЯ СИЛЬНОСТРУМОВИМИ ЕЛЕКТРОННИМИ ПУЧКАМИ ВЕЛИКОЇ ПЛОЩИНИ

***О. Гончаров, А. Добровольський, І. Літовко, В. Гушенець, Є. Окс, О. Бугаєв***

Представлено нові теоретичні та експериментальні результати дослідження фокусування сильнострумового інтенсивного електронного пучка плазмовою лінзою з хмарою аксіально-симетричного позитивного просторового заряду, створеного циліндричним прискорювачем з анодним шаром та магнітною ізоляцією електронів. Досягнуто майже 30-кратне збелічення густини струму пучка на осі при сумісної дії магнітного та електростатичного полів лінзи. Запропоновано модифіковану конструкцію плазмової лінзи, яка усуває моментні аберації.